Cooperative Load Balancing in IEEE 802.11 Networks with Cell Breathing

Eduard Garcia Rafael Vidal Josep Paradells
Wireless Networks Group - Technical University of Catalonia (UPC)
{eduardg, rvidal, teljpa}@entel.upc.edu; +34 934137218

Abstract

IEEE 802.11 WLANs (Wi-Fi) are widely deployed for providing Internet access in public spaces, known as Hot Spots. In these scenarios, users tend to be "gregarious" and essentially static. Since association and roaming decisions are made by client devices following signal strength criterions (i.e. a client station selects the AP that provides the strongest signal), the users and their load are unevenly distributed between neighboring APs. In this paper we propose a distributed algorithm with which the APs in an IEEE 802.11 WLAN are able to tune their cell size according to their load and also to their neighbor's load. This technique improves the fairness and the performance levels and is known as Cell Breathing.

1. Introduction

It could be said that WLANs based on the IEEE 802.11 set of standards are victims of their own success. The great popularity of these networks has led to its expansion in scenarios for which they had not been originally designed (e.g. mesh topologies, large scale networks, outdoor links, etc.). For example, various studies have shown (e.g. see [1]) that users tend to be concentrated both temporally and spatially, creating highly congested areas known as Hot Spots. Therefore, the load is unevenly distributed across a small number of Access points (APs) in the WLAN. Moreover, although mobility is increasing as users get into the habit of using wireless access, the mobility pattern can still be considered quasi-static in the sense that users tend to remain in the same location for long periods. This situation is compounded by the fact that the association with base stations is determined by the client devices on the basis of signal level measurements, which means that users are generally associated with the closest AP. In other words, although a Hot Spot is served by several APs, most of the users will be connected through the AP that provides the strongest signal. As an inherent consequence, over-loaded APs offer the users in congested areas a very low QoS while nearby APs remain under-utilized. This behavior is determined by the roaming process, which goes as follows [2].

A station (STA) keeps track of the Beacon frames received from its current AP. When the quality of beacons drops below the cell search threshold ($10< CS_{Th}<30$dB), the STA initiates an active scan and sends out Probe Request messages on all the available channels. The APs receiving the Request will send a Probe Response back. When an AP is found whose responses improve the current AP's Beacons quality by at least ΔSNR (usually $6 \leq \Delta SNR \leq 8$ dB), the STA initiates a cell switch. If a better candidate is not found, the STA returns to the current AP's channel and the scan sweep is repeated periodically.

There are different solutions to the unfair situation explained above, the most evident of which consists of using a different roaming criterion (e.g. AP load), but it requires deep changes in client devices. We choose to keep any modification transparent to the end user who can be equipped with off-the-shelf devices. For these reasons, in this paper we propose a new AP-driven load balancing scheme based on cell breathing, intended to alleviate the congestion in hot spots: congested APs reduce the size of their cells; alternatively, under-utilized APs increase their cells to attract further stations. In our approach, neighboring APs cooperate in order to improve performance and fairness levels. To this aim, APs can make use of the information available to client stations through the mechanisms provided by the new IEEE standards: 802.11e, 802.11h and, principally, 802.11k.

The rest of the paper is structured as follows: Section 2 discusses the definition of load in the particular case of 802.11 WLANs. Section 3 provides an overview of related work. In Section 4 we describe our algorithm. Section 5 discusses some implementation issues. Section 6 contains an evaluation of our proposal in comparison with other schemes; finally, conclusions are given in Section 7.

2. Definition of load

Load balancing in overlapping areas has traditionally been used in circuit-switched cellular networks. Since each user in these types of networks represents an identical utilization of available resources, load

978-1-4244-2703-1/08/$25.00 ©2008 IEEE

balancing could be applied by using call level information, i.e. load is represented by the number of active calls served by a BS.

Nevertheless, call level information is not sufficient for modeling the actual load that is carried by a BS in current wireless packet networks, given that users may have different traffic profiles. This assertion is valid for IEEE 802.11 WLANs. Therefore, a new metric based on packet level information is required. However, the number of active users still provides valuable information in networks that use CSMA-based access: more collisions occur as the number of active users increases, which leads to decreased performance. The number of competing stations can be calculated from any station by using the formulation given in [3], but this parameter can only be used to estimate the saturation throughput of a cell and does not provide information about the actual load.

Different load metrics based on packet level information have been proposed. The authors of [4] used the number of retransmission attempts needed to successfully transmit a single packet, which can be derived if all hidden pairs are known. The same concept was also used in [5] to derive the Gross Load metric using a different formulation. Reference [5] also suggests using the packet loss estimation as a new load metric. Traffic (in bytes/s) was used as a load metric in [6] and [7]. However, we should bear in mind that the IEEE 802.11 standards define several modulations with different physical bit rates (e.g. 1, 2, 5.5 and 11 Mbps for 802.11b); in this case an AP could be congested when carrying traffic of 1 Mbps if there are associated stations transmitting at the slowest bit rate. On the other hand, the same AP could also be considered under-utilized with a load of 3 Mbps if all of its clients use faster modulations. Therefore, carried traffic is not a valid representation of the load on an AP in a multi-rate scenario. Instead, in [8] and [9] the measure of busy time is proposed as the representative load metric. More precisely, in [9] the network congestion level is estimated using channel occupation time and by monitoring the occupation of the AP's buffer queue.

2.1 Load information in new IEEE standards

The IEEE 802.11k group (Radio Resource Measurement) is currently developing a standard which is intended to improve the provision of data from the physical and medium access layers by defining a series of measurement requests and reports that can be used in the upper layers to carry different radio resource management mechanisms. The current draft version is 9.0 [10], although the final standard is expected to be released soon (at the time of writing).

The current IEEE 802.11 standard [11] and the future 11k define a set of load metrics that are either broadcast by APs or measured directly by client stations:

Channel Load Report: defined as the proportion of the time during which either the physical carrier sense, the virtual carrier sense (Network Allocation Vector or NAV) indicate that the channel is busy. This measurement is similar to the CCA report in 802.11h.

Beacon Frames: these management frames are extended with three new elements that provide information about the load of an AP.

- *BSS Average Access Delay*: average medium access delay for any transmitted frame measured from the time the frame is ready for until the actual frame transmission start time.
- *BSS AC Access Delay*: in QAPs (QoS enabled APs), average medium access delay for each of the indicated Access Categories defined by the IEEE 802.11e.
- *BSS Load* includes the following fields:
  - *Station Count*: the number of stations currently associated with the AP.
  - *Channel Utilization*: the percentage of time that the AP senses the medium is busy.
  - *Available Admission Capacity* (AAC): the remaining amount of medium time available via explicit admission control.

Although channel busy time provides a good representation of the cell load even in a multi-rate scenario, we consider that it is not a valuable metric in the presence of greedy applications (e.g. FTP). For example, a channel busy time of 85% can be achieved with a single greedy station, but also with 10 users offering 500kbps each. However, a new station will get much more bandwidth if it only has to compete with one user than if it has to share the medium with 10 other stations. The advantage of AAC over access delay resides in its ability to anticipate the potential effects on load and throughput of adding a new user.

The IEEE 802.11 standard defines AAC as the remaining amount of medium time available in units of 32 µs, although it does not specify how it should be calculated. In [12] we proposed a new load metric based on a more precise definition of AAC. We expand the current definition of Available Admission Capacity to be the proportion of time a new station can take up if it is associated with the AP at a given physical rate. This new metric provides a vision of cell load that takes into account the effect of multi-rate stations, the presence of greedy users, the average frame size, the number of active users and also transmissions errors and collisions. Any AP can easily derive its AAC value by inspecting statistics that are usually provided by the wireless interface driver. For details on AAC derivation and implementation issues see [12].

3. Load Balancing in WLANs

Different approaches have been proposed in the literature that try to change the client-driven nature of IEEE 802.11 association and roaming decisions. The authors of [6] and [8] propose network-controlled schemes in which client stations send the required information to a central unit, which also has access to the load information for each cell. The scheme proposed in [6] provides the best AP for association and the network also suggests roaming to APs located further away if nearby APs are considered unable to cover the station's requirements. In order to implement these solutions it is necessary to modify the client devices: firstly, they have to send new management frames before they are actually associated; secondly, they will no longer be responsible for association or roaming decisions. The first issue can be solved by using new radio measurements (e.g. IEEE 802.11k). Reference [13] provides a survey of different load balancing techniques and discusses the applicability of the new 11k procedures. However, there is no standardized procedure for solving the second issue as yet, but it is expected to be revised by the IEEE 802.21 group, which will provide mechanisms intended to assist handovers, and by IEEE 802.11v, which will include management capabilities to allow network-directed roaming.

It is not vital to solve the second of these issues, since it is also possible to perform implicit admission control/association management. This involves actions taken on the network side that induce the desired client behavior and therefore leave the roaming and association decisions to client stations so that hardware/software modifications are not required. In [9] the APs accept or deny new association requests depending on the respective load. When the first choice is rejected, the stations will send association requests to the next AP in the signal strength-arranged list, until they are admitted. The algorithm proposed in [7] is more sophisticated but follows similar logic. There are three possible AP states: under-loaded (will accept any request), balanced (will not accept extra load) and over-loaded (will expel the station on the assumption that it will automatically request a less loaded AP).

Cell breathing is a side effect in CDMA networks that reduces the cell coverage when more users are supported, but this could be advantageous in load balancing techniques if optimal strategies are applied. Cell breathing techniques consist in dynamically modifying cell dimensions usually increasing or reducing transmitted power. The concept of cell breathing for load balancing in WLANs is explained in [14]: a highly congested AP reduces its coverage radius so that the furthest stations lose connectivity and try to roam to a neighboring AP (less loaded). An under-utilized AP may increase its transmit power in order to expand its coverage. Consequently, new users will roam to this AP and the load on neighboring APs will decrease. In [15], APs could even build a custom radiation pattern to balance load, but besides a very specialized RF hardware, this solution relies on the APs' perfect knowledge of their own coverage and the exact position of clients, which is hardly feasible. Reference [16] provides an in-depth analysis of cell breathing in IEEE 802.11 WLANs and proposes a centralized solution based on two different algorithms: one is aimed to reduce the load of the most congested AP and the other tries to find the min-Max load balanced solution. However, as stated in [13], the furthest stations may sometimes be expelled arbitrarily as they may contribute an insignificant load depending on the applications they run. On the other hand, cell breathing provides a network-induced association management and therefore it does not generally require any change on client devices.

4. Distributed load balancing algorithm with cell breathing

We have to distinguish between two independent types of transmitted power management: cell dimension management (Cell Breathing) and transmitted power control (TPC). As previously explained, Cell Breathing tries to improve load balancing among neighboring APs, while TPC is aimed to reduce power consumption, interference and the near-far effect [17].

From the client station's point of view, the cell dimensions are determined by the energy of received Beacon frames and Probe Responses. Then, an AP can set its optimal cell dimension so that the farthest client that the AP must serve, receives Beacons with $SNR > CS_{Th}$. But, as in [16], the power used to transmit data frames can be higher so that the user's experience is not degraded. Hence, an optimum TPC algorithm is assumed (e.g. [18][19]) for the exchange of data frames between an AP and its clients, using the minimum power that does not degrade the performance of the communication. For this reason we distinguish between tx range (determined by the maximum transmission power allowed) and cell size (determined by beacons and Probe Responses).

In our approach, APs are responsible for computing their own load and let their neighbors know about it by either periodic or triggered updates. Similar to [7], APs can be in one of the following three states, according to their load, as compared with their neighbors':

- ***Fair***: the AP's load is similar to the average load in the neighborhood. An AP in this state will not take any action regardless of its neighbor's behavior.
- ***Gull***: the AP's load is larger than the average load in the neighborhood. An AP in this state is willing to

reduce its cell and will try ask its neighbors for help.

- ***Willing***: the AP's load is below the average load in the neighborhood. An AP in this state is willing to increase its cell in response to a neighbor's appeal.

In order to determine the AP's load we propose the AAC metric, defined as the capacity available for a new station that uses the fastest modulation [12]. Logically, as the congestion increases, the APs' AAC decreases. Then, we consider that an AP i is ***Gull*** if $AAC_i < \overline{AAC_i} - \delta$, where AAC_i is the capacity available in AP i, $\overline{AAC_i}$ is the average capacity in i's neighborhood and δ a threshold value used to add hysteresis, thus improving the stability of the system. Analogously, an AP i is ***Willing*** if $AAC_i > \overline{AAC_i} + \delta$. If none of the previous conditions is met, the AP is in state ***Fair***. The value of δ is set dynamically according to $\overline{AAC_i}/3$. The optimum value was chosen after a previous simulation-based study that is not detailed here for the sake of brevity. Two APs are neighbors if there is at least one client within transmission range of both APs.

The behavior of ***Gull*** and ***Willing*** APs is detailed in figure 1. Note that initial and final states are connected

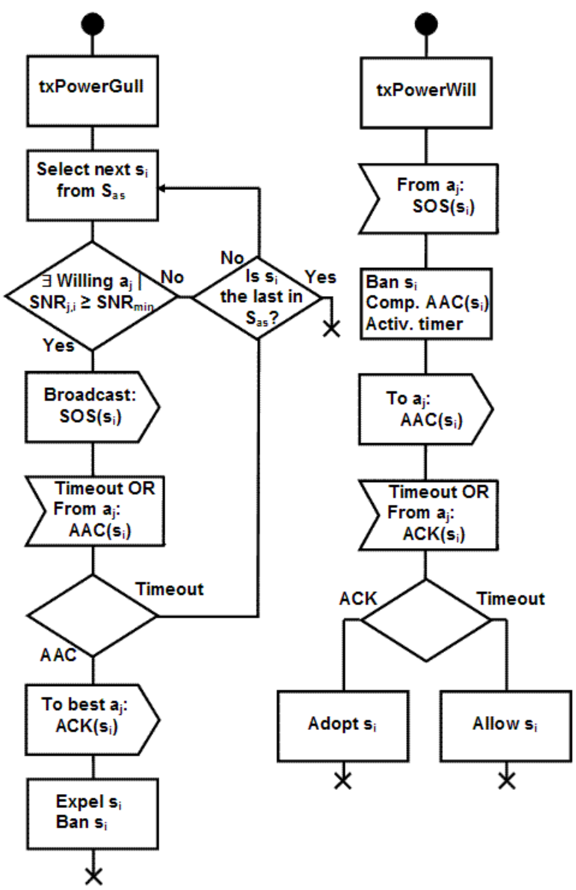

Fig. 1: Behavior of **a)** a ***Gull*** AP, and **b)** a ***Willing*** AP

and that the process can be interrupted if the state of the AP changes. The first action taken by an AP is to arrange its cell size according to its state. ***Fair*** and ***Gull*** APs will run *txPowerGull()* to reduce the size of their cells so that the client receiving the poorest signal detects beacons with $SNR > CS_{Th}$, or the minimum transmission power is reached; ***Fair*** APs will not take any further action. A ***Willing*** AP will run *txPowerWill()* increasing its cell size so that no STA associated to a neighboring AP roams to it, or the maximum transmission power is reached.

We define S as the set of STAs (s_i) and A the set of APs (a_j); S_{as} is the subset of the elements of S that contains the STAs associated to a given AP a_j, and S_{rg} is the list of STAs within a_j's range. Both lists are arranged in decreasing order according to the SNR computed from a_j's beacons. $SNR_{j,i}$ is the SNR of aj's beacons as seen from s_i, while SNR_i is the SNR of the beacons that s_i receives from its current AP. Then, for any a_j:

$$S_{rg}^{j} = \{s_i \forall i \in S \mid SNR_{j,i} > SNR_{\min}\}$$

$$S_{as}^{j} = \{s_i \forall i \in S \mid SNR_{j,i} > SNR_{k,i} \forall k \in A\}$$

We assume that S_{as} and S_{rg} are always updated thanks to the complete collection of statistics provided by an independent process (see next section). A ***Gull*** AP will then select the first s_i from its S_{as} that is able to roam to a ***Willing*** AP. The ***Gull*** AP will send an *SOS* message to all APs within range of s_i. A ***Willing*** AP receiving a *SOS* message will compute the AAC value for that particular STA and will forward this value to the requesting ***Gull*** AP. This AAC is computed taking into account the fact that an optimal TPC is used for data exchange. The ***Gull*** AP then sends an acknowledgement only to the best AP candidate and adjusts its cell size expelling the selected STA (s_i). In turn, the adoptive AP adjusts its cell size to accommodate s_i. In order to avoid undesired handovers, all APs receiving a SOS message will ban the announced s_i (e.g. via ACL) until the process is complete.

5. Implementation Issues

Although the algorithm presented in this paper has not been fully implemented, some of the functionalities required have been previously tested in real testbeds. For example, the signaling required to communicate neighboring APs could be easily carried out by means of a common wired backbone. If there is no such common backbone, APs could still participate in the distributed algorithm using a wireless distribution system based on mesh concepts as proposed in [20].

As in [16] and [18], one of the requirements for the APs is the possibility to set the transmission power in a per-packet manner. In this way, APs can arrange their

```
Function txPowerWill:

end = false

while !end do
   if Ptx + step > PtxMax
      then end = true

   for all S_i ∈ S_rg do
      if SNR_i < CS_th AND
      if SNR_j,i > SNR_i + ΔSNR + step
         then end = true
   done

   if !end
      then Ptx = Ptx + step
done
```

```
Function txPowerGull:

end = false
MaxSNR_i = Max(SNR_k,i ∀ k ∈ A)

while !end do
   if Ptx - step < PtxMin
      then end = true

   for all S_i ∈ S_gs do
      if SNR_i < CS_th AND
      if SNR_i –step < MaxSNR_i + ΔSNR
         then end = true
   done

   if !end
      then Ptx = Ptx - step
done
```

cell size adjusting the transmitted power for Beacons and Probe Responses and at the same time running an effective TPC for data. The AAC computation adds another requirement for the APs: an updated collection of statistics is required at application level in order to allow the AAC estimation in real time. It is worth to mention that the extra processing load introduced by the AAC computation is affordable despite the AP's limited resources, as stated in [12].

Nevertheless, the information needed by the APs to run the algorithm described in the previous section represents the main implementation issue. Any AP should know the complete list of STAs within transmission range and the list of APs that any of these STAs can reach, including SNR of beacons and potential SNR for data. The new standard [11], which includes the 802.11h amendments, along with the upcoming 802.11k standard [10] will ease the acquisition of this information, as detailed next.

The potential SNR for data exchange between an AP and all the client STAs in range can be obtained by means of an 11h's *TPC Request/Report* or an 11k's *Link Measurement Request/Report*. These two mechanisms are similar and allow the estimation of the link margins between two stations. The requesting AP announces the transmitted power used to send the request (maximum allowed transmitted power) and the requested STA responds with the link margin according to the SNR of the received request. The response also includes the transmitted power used to send the frame. APs are also able to retrieve information about the SNR of received beacons using the *Beacon Request/Report* defined in 802.11k. A STA receiving a *Beacon Request* will respond with a *Report* containing statistics, including SNR, power, channel and BSSID, of received Beacons and Probe Responses. The AP still has to know the potential SNR for data between its in-range STAs and the neighboring APs. This could be solved either adding an extra signaling among APs or independently, using the 802.11k frames: *Measurement Pilot*. Similarly to Beacons, these frames are transmitted pseudo-periodically by APs at a small interval, but a *Measurement Pilot* is smaller than a Beacon and is transmitted more often than a Beacon. STAs also include statistics of received *Measurement Pilots* in *Beacon Reports*, so, if APs send these frames at the maximum allowed transmission power, APs could finally gather all required information.

However, our approach is also feasible with no 802.11k enabled devices. We have to note that in this case, many of the parameters can only be approximated and that it is required that STAs perform active scans. In this way, all APs within the STA's range are able to obtain the uplink margin from Probe Request messages, and thus estimate the downlink margin assuming that the path is symmetric and that the power used to send the Probe message is known (max. allowed power). These assumptions also allow APs to estimate the power of received Beacons (knowing the power of transmitted Beacons and the estimated path loss). Furthermore, more signaling is required to exchange this information among APs.

6. Performance Evaluation

6.1 Scenario

The evaluation process we designed is based on extensive simulations in a 380x380 m square indoor scenario with 16 IEEE 802.11b APs evenly distributed. The simulator was developed in C and implements all the details of the algorithms described in 4. We ran a large number of independent simulations and obtained small confidence intervals, which are therefore not shown in the figures. The throughput carried by an AP and the throughput available to the STAs is computed according to the model presented in [12].

Using a path loss $PL(d)$ = 40-33·log(d), where d is de distance between a transmitter and a receiver, $ptxMax$=15dBm and a $ptxMin$=10dBm (highest and lowest allowed transmission power), we assume that with all APs transmitting at $ptxMin$, there is no coverage gap in the scenario, and that transmitting at $ptxMax$ no

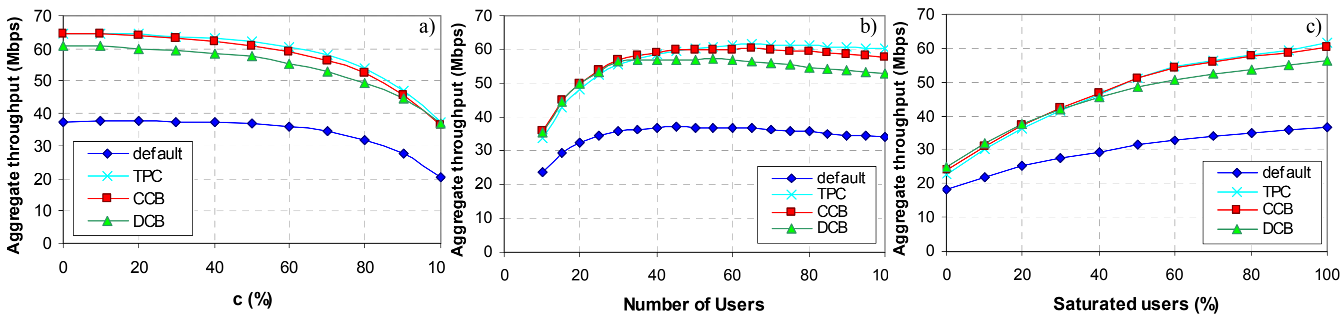

Figure 2: Aggregate throughput: **a)** 65 saturated STAs. **b)** Saturated STAs and c = 55%. **c)** 65 STAs and c = 55%

co-channel interference is produced (using a 4-coloring scheme). As stated in [1], users are static and tend to be spatially concentrated. We simulate these characteristics by placing users at random, but forcing that a given percentage of users, *c* %, are concentrated in a randomly selected area of 100x100 m. This ensures that a realistic scenario is met. The physical rate used for data transmissions depends on the distance between an STA and its selected AP: if d < 46m, rate = 11Mbps; if d < 61m, rate = 5.5Mbps; if d < 75m, rate= 2Mbps; and if d < 92m, rate = 1Mbps. For $d \geq$ 92m SNR_{min} = 1dB is not met. Finally CS_{Th} = 20 dB and ΔSNR = 7 dB. The PER of each STA depends on the SNR and modulation used for data transmissions, according to the performance of an Intersil Prism HFA3863 [21]. A collision probability is also provided for each cell, depending on the number of active users (see [3]).

Our approach (Distributed Cell Breathing – DCB) is compared against different mechanisms. The centralized approach (CCB) of [16] is used as a reference since, as we understand, a complete knowledge of the scenario will allow better assignments. Both DCB and CCB use AAC as the load metric. We call TPC the solution that implements solely an optimal TPC for data exchange, but that keeps the size of the cells fixed. Finally, the default behaviour of current IEEE WLANs is also represented in the simulations.

6.2 Simulation results

The first conclusion derived from the simulations was that the proposed algorithm runs without loops, and converges rapidly in the scenario depicted in the previous subsection. Then we measured the aggregate throughput in different situations. Figure 2 a) and b) are obtained in saturation conditions, that is, all STAs have always buffered frames (1500 Bytes) ready for transmission. Figure 2 a) shows the effects of increasing the concentration (*c* %) with a fixed number of users (65), while b) has a fixed *c* (55%) and a varying number of users. It is not a surprise that the TPC solution presents the best results, since it always guarantees that all STAs use the best possible rate. In the case where STAs have different traffic profiles (packet size from 500 to 1000 Bytes and offered load ranging from 0.2 to 2Mbps), DCB outperforms the other approaches (see Figure 2 c), but as the number of saturated users increase, it becomes slightly worse. The aggregate throughput has a maximum with 3 or 4 STAs per AP and decreases with more users due to the increasing collision probability. Logically, as *c* increases (more users use less APs), the aggregate throughput decreases.

However, a maximized aggregate throughput does not involve that the throughput of all STAs is maximized. For this reason we also measured the fairness degree among STAs and among APs. Fairness is measured using the known Jain's Index: β is a value between 0 (unfair) and 1 (fair):

$$\beta = \frac{\left(\sum_{i}^{n} r_i\right)^2}{n\sum_{i}^{n} r_i^2}; 0 \leq \beta \leq 1$$

When we measure fairness among STAs, r_i is the traffic carried by STA *i* and *n* is the number of STAs. When we measure fairness among APs, r_i is the AAC of AP *i* and *n* is the number of APs. We observed that DCB presents the best fairness values in all the cases, regardless of the number of users, *c* or number of STAs in saturation (e.g. see figure 3). Another measure of fairness can be provided by measuring r_{i_min}. In this case, since CCB is designed to maximize AAC_{min}, its results are logically the best (see Figure 4a). But although CCB also provides the highest minimum carried throughput on average, (as shown in figure 4b), we have to note that DCB provided the best results in most of the simulations.

7. Conclusions

In this paper we have presented a new distributed load balancing algorithm for IEEE 802.11 WLANs, based on the idea of cell breathing. In our approach, the APs have the ability to cooperate in order to redistribute the load among neighboring cells, in a way that is transparent to the end user, who can be equipped with standard devices. The most obvious conclusion that can

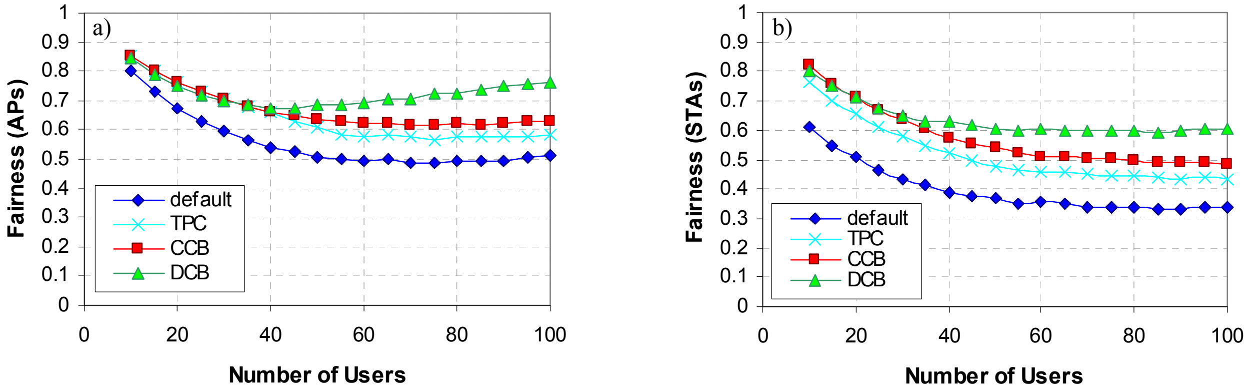

Figure 3: Jain's Fairness index for **a)** APs and **b)** STAs. STAs in saturation and c = 55%

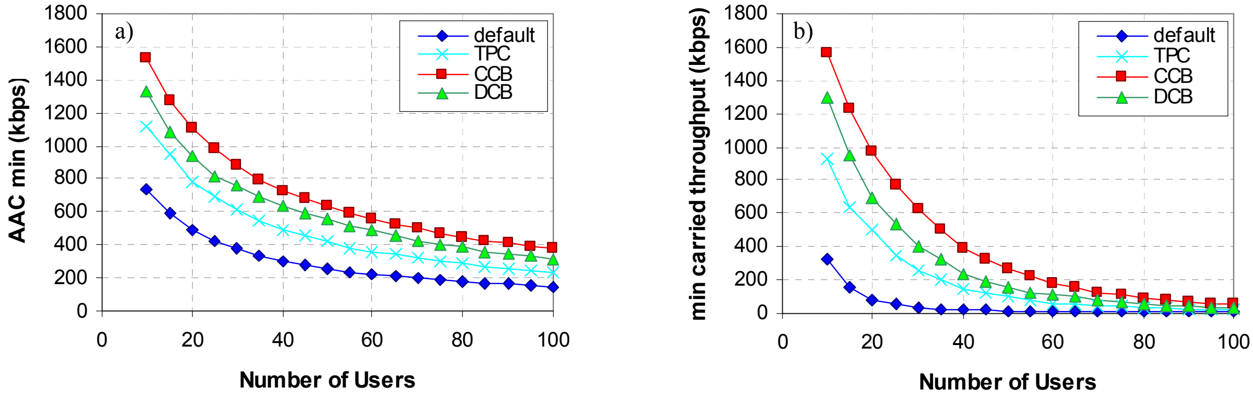

Figure 4: **a)** min AAC for an AP. **b)** min carried throughput for a STA

be derived from the evaluation is that the absence of any kind of power control reduces the potential capacity of the network drastically. Applying an optimal TPC for data exchange ensures a better utilization of the resources and therefore, the performance of the network is improved. However, in scenarios with a high density of nodes, the average user experience can be further improved, and the congestion level on APs alleviated, if we introduce the ability to dynamically change the cell size according to the environment. Our approach not only provides good network performance but also ensures an even share of bandwidth among clients and a balanced load among APs.

Although it is not a strong requirement, the main implementation issue arises with the need to exchange information between client stations and APs. Since the needed information exchange is related to radio measurements, this requirement will be satisfied with the advent of new IEEE standards: IEEE 802.11h and 802.11k.

Acknowledgment

This research work was funded by the ERDF, the Spanish Government through TEC2006-04504, and the i2CAT foundation.

References

[1] T. Henderson, D. Kotz, and I. Abyzov, "The changing usage of a mature campus-wide wireless network," in *10th Mobicom*, pp. 187-201, September 2004.

[2] N. Prasad, A. Prasad, "WLAN Systems and wireless IP for next generation communications", Artech House, 2001.

[3] G. Bianchi and I. Tinnirello, "Kalman Filter estimation of the number of competing terminals in an IEEE 802.11 network," in *22nd Annual Joint Conference of the IEEE Computer and Communications Societies, INFOCOM'03*,vol. 2, pp. 844-852, April 2003.

[4] I. B. Dhou, "A Novel Load-Sharing Algorithm for Energy Eficient MAC Protocol Compliant with 802.11 WLAN," in *IEEE 50th Vehicular Technology Conference, VTC 1999-Fall*, vol. 2, pp. 1238{1242, September 1999.

[5] G. Bianchi and I. Tinnirello, "Improving Load Balancing Mechanisms in Wireless Packet Networks," in *IEEE International Conference on Communications 2002, ICC 2002*, vol. 2, pp. 891-895, April 2002.

[6] A. Balachandran, P. Bahl, and G. M. Voelker, "Hot-Spot Congestion Relief in Public-area Wireless Networks," in *Proc. of 4th IEEE Workshop on Mobile Computing Systems and Applications*, pp. 70-80, June 2002.

[7] H. Velayos, V. Aleo, and G. Karlsson, “Load balancing in overlapping wireless LAN cells," in *IEEE International Conference on Communications, 2004. ICC'04*, vol. 7, pp. 3833-3836, June 2004.
[8] Y. Bejerano, S.-J. Han, and L. E. Li, “Fairness and load balancing in wireless LANs using association control," in *Proc. of the 10th international conference on Mobile computing and networking, MobiCom'04*, pp. 315-329, 2004.
[9] A. Bazzi, M. Diolaiti, and G. Pasolini, “Measurement based Call Admission Control Strategies in Infrastructured IEEE 802.11," in *The 16th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC 2005.*, September 2005.
[10] IEEE 802.11 WG. *Draft Supplement to Standard for Telecommunications and Information Exchange Between Systems—LAN/MAN Specific Requirements—Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Specification for Radio Resource Measurement, IEEE 802.11k/D9.0*. New York, USA: The Institute of Electrical and Electronics Engineers, Inc., September 2007.
[11] IEEE 802.11 WG. *IEEE Standard for Telecommunications and Information Exchange Between Systems—LAN/MAN Specific Requirements—Part 11: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications*. New York, USA: The Institute of Electrical and Electronics Engineers, Inc., June 2007.
[12] E. Garcia, D. Viamonte, R. Vidal and J. Paradells, “Achievable bandwidth estimation for stations in multi-rate IEEE 802.11 WLAN cells”, in *proceedings of IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, WoWMoM07*, June 2007.
[13] E. Garcia, R. Vidal and J. Paradells, “Load Balancing in WLANs through IEEE 802.11k Mechanisms,” in *Proceedings of the IEEE Symposium on Computers and Communications (ISCC'06)*, pp. 844-850, June 2006.
[14] O. Brickley, S. Rea, and D. Pesch, “Load Balancing for QoS Optimisation in Wireless LANs Utilising Advanced Cell Breathing Techniques," in *IEEE 61st Vehicular Technology Conference, 2005. VTC 2005-Spring*, May 2005.
[15] Y. Wang, LG. Cuthbert and J. Bigham, “Intelligent Radio Resource Management for IEEE 802.11 WLAN”, in *IEEE Wireless Communications and Networking Conference, WCNC04*, vol. 3, pp. 1365-1370, March 2004.
[16] Y. Bejerano and S-J. Han, “Cell Breathing Techniques for Load Balancing in Wireless LANs,” in *Proceedings of the 25th IEEE Annual Conference INFOCOM'06*, April 2006.
[17] D. Qiao, and S. Choi, “New 802.11h Mechanisms Can Reduce Power Consumption,” in *IT Professional,* vol. 8, 2, pp. 43-48, March 2006.
[18] D. Qiao, S. Choi, A. Jain and KG. Shin, “MiSer: an optimal low-energy transmission strategy for IEEE 802.11a/h,” *Proceedings of the 9th annual international conference on Mobile computing and networking, MobiCom03*, pp. 161-175, 2003.
[19] J. Rao, S. Biswas, “Transmission power control for 802.11: a carrier-sense based NAV extension approach,” *IEEE Global Telecommunications Conference, GLOBECOM 05*, vol. 6, pp. 3439-3444, November 2005.
[20] E. Garcia, L. Faixó, R. Vidal, J. Paradells, “Inter-Access point communications for distributed resource management in 802.11 networks,” *4th ACM Workshop on Wireless Mobile Applications and Services on WLAN Hotspots, WMASH06*, p. 11-19, 2006.
[21] *HFA3863: Direct Sequence Spread Spectrum Base-band Processor with Rake Receiver and Equalizer*. Data Sheet. Intersil Inc., December 2001.